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Abstract: The environmental and economic impact of fruit and vegetable waste (FVW) valorisation on an industrial scale was estimated by applying the "multi-objective method". To this aim, the lettuce waste study-case was considered, since different innovative laboratory-scale strategies have been recently proposed for its valorisation. Investment and running costs, energetic demand and yields of lettuce waste valorisation processes were collected based on laboratory tests and industrial surveys. The application of the multi-objective method estimated that if 20% of lettuce waste annually produced by a large company was valorised, it would present an investment lower than 10 million €, a 1 year-pay-back time and a 72 tons-reduction of carbon dioxide emissions, thus representing a rational compromise between economic returns and environmental advantage. The multi-objective method can be used to develop a decision support system to identify the most sustainable and worthy-of-investment processes for FVW valorisation.

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Evaluating the environmental and economic impact of fruit and vegetable waste valorisation: the lettuce waste study-case

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Dear Editor,

We send to your attention the research article entitled "**Evaluating the environmental and economic impact of fruit and vegetable waste valorisation: the lettuce waste study-case**" Stella Plazzotta, Mattia Cottes, Patrizia Simeoni and Lara Manzocco. All the authors have read and approved the manuscript. Following, we report the abstract.

The environmental and economic impact of fruit and vegetable waste (FVW) valorisation on an industrial scale was estimated by applying the “multi-objective method”. To this aim, the lettuce waste study-case was considered, since different innovative laboratory-scale strategies have been recently proposed for its valorisation. Investment and running costs, energetic demand and yields of lettuce waste valorisation processes were collected based on laboratory tests and industrial surveys. The application of the multi-objective method estimated that if 20% of lettuce waste annually produced by a large company was valorised, it would present an investment lower than 10 million €, a 1 year-pay-back time and a 72 tons-reduction of carbon dioxide emissions, thus representing a rational compromise between economic returns and environmental advantage. The multi-objective method can be used to develop a decision support system to identify the most sustainable and worthy-of-investment processes for FVW valorisation.

We hope that this article could satisfy the requirements of Journal of Cleaner Production, so that you might consider it for publication in this Journal.

Best regards,

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Highlights (for review)

- Different valorisation strategies can be applied to fruit and vegetable waste (FVW)
- The multi-objective method can estimate sustainability of FVW valorisation
- FVW valorisation sustainability estimate requires quantitative industrial-scale data
- Multiple FVW valorisation strategies can be applied to reach sustainability

Figure

<table>
<tr><th>Phase</th><th colspan="4">Description</th><th>Output</th></tr>
<tr><td>Investigative</td><td colspan="4">Data collection using tools of Life Cycle Analysis and techno-economic and profitability assessment</td><td>Waste amount quantification
Industrial park layout
Energy and cost functions
Environmental advantage indexes
Economic profitability indexes</td></tr>
<tr><td>Design</td><td>Stage</td><td>Objective</td><td>Tool</td><td>Done by</td><td></td></tr>
<tr><td></td><td>Design of experiment (DOE)</td><td>To classify system variables and define system constraints</td><td>DOE algorithms</td><td>Mode Frontier</td><td>Input and output variables; model constraints</td></tr>
<tr><td></td><td>Computation</td><td>To calculate the value of output variables as a function of input ones, under defined constraints</td><td>Mathematical Model</td><td>Microsoft Excel</td><td>Possible scenarios</td></tr>
<tr><td></td><td>Scheduling</td><td>To order the obtained scenarios depending on the value of output variables</td><td>Scheduling algorithm</td><td>MatLab</td><td>Scheduled scenarios</td></tr>
<tr><td>Scenario analysis</td><td colspan="4">Analysis of possible scenarios</td><td>Scenarios allowing the objectives of the study to be reached</td></tr>
</table>

Figure 1. Structure of the decision support system.

Figure

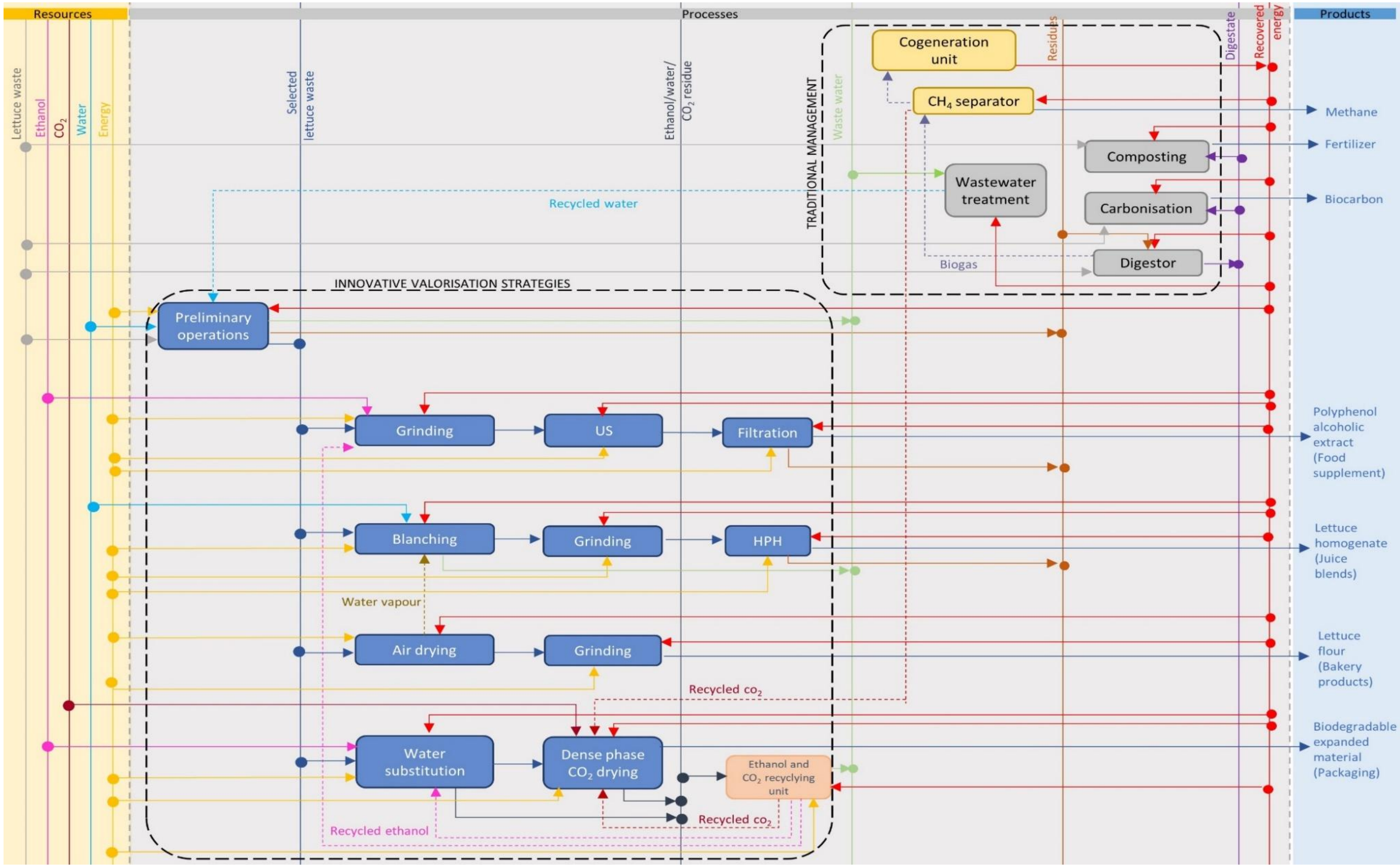

Figure 2. Flow diagram of resources (lettuce waste, ethanol, carbon dioxide, water and energy) in an industrial park integrating traditional management and innovative valorisation strategies of lettuce waste.

Table 1. Yields and outputs of processes involved in traditional management and innovative valorisation of lettuce waste and in related side activities. Output intended use and unit price range are also reported.

Strategy	Process	Yield (%)	Output	Intended use	Price per unit range (€/kg)
Traditional management	Anaerobic digestion	3	Biogas	Fuel for cogeneration	Rec.
	Cogeneration	60	Pure methane	Energy	Rec.
	Composting	30	Fertilizer	Fertilizer	Rec.
	Carbonization	10	Biocarbon	Fuel	0.25-0.90
Innovative valorisation	Preliminary operations	<50	Selected lettuce waste	Raw material for valorisation strategies	Rec.
	Bioactive extraction	80	Lettuce bioactive extract	Food supplement	9.00-18.00
	Homogenisation	85	Lettuce homogenate	Ready-to-eat soups and juice blends	3.00-6.00
	Flour production	5	Lettuce flour	Functional bakery products	0.80-1.60
	Supercritical-CO_2-drying	5	Lettuce material	Biodegradable expanded material for packaging applications	0.03-0.18
Side activities	Ethanol recycling	80	Ethanol	Resource for industrial facilities	Rec.
	Carbon dioxide recycling	80	Carbon dioxide	Resource for supercritical-CO_2-drying	Rec.
	Wastewater treatment	60	Water	Resource for industrial facilities	Rec.

Rec. = Recycle within the industrial park

Table 2. Possible scenarios of lettuce waste valorisation, according to the main study objectives.

Objective	**Processed waste (%, w/w)**							**Reduction of greenhouse gas emission (tons CO_2/year)**	**Saved energy (tons of oil equivalent/year)**	**Investment (€)**	**Payback time (years)**
	Traditional management			**Innovative valorisation**							
	Carbonisa-tion	Compo-sting	Anaerobic digestion	Lettuce flour	Lettuce homogenate	Lettuce bioactive extract	Lettuce material				
Maximisation of environmental advantage	0	0	60	0	4	24	12	124.4	55.1	9,667,276	2.4
Minimization of investment cost	70	0	20	0	1	9	0	39.1	17.3	8,502,699	3.1
Minimization of pay-back time	20	10	0	0	0	70	0	63.1	28.0	10,535,299	0.3
Compromise	0	40	30	0	12	18	0	71.8	31.8	9,120,427	1.0

Supplementary File
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Supplementary File

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Evaluating the environmental and economic impact of fruit and vegetable waste valorisation: the lettuce waste study-case

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Abstract

The environmental and economic impact of fruit and vegetable waste (FVW) valorisation on an industrial scale was estimated by applying the "multi-objective method". To this aim, the lettuce waste study-case was considered, since different innovative laboratory-scale strategies have been recently proposed for its valorisation. Investment and running costs, energetic demand and yields of lettuce waste valorisation processes were collected based on laboratory tests and industrial surveys. The application of the multi-objective method estimated that if 20% of lettuce waste annually produced by a large company was valorised, it would present an investment lower than 10 million €, a 1 year-pay-back time and a 72 tons-reduction of carbon dioxide emissions, thus representing a rational compromise between economic returns and environmental advantage. The multi-objective method can be used to develop a decision support system to identify the most sustainable and worthy-of-investment processes for FVW valorisation.

Key-words: Fruit and vegetable waste; food waste; valorization; feasibility; sustainability; decision support system

1. Introduction

Fruit and vegetable waste (FVW) valorisation has been extensively and increasingly studied in the last years, as evidenced by the enormous number of relevant publications (Supplementary Figure S1). Despite this intense research activity, the current destination of FVW is mainly represented by landfilling, composting, anaerobic digestion and carbonisation (Cristóbal et al., 2018). However, when FVW is used this way, as a feedstock to produce energy and fertilizers, its interesting functional molecules are underutilised or lost (Pfaltzgraff et al., 2013). The latter are instead maximally exploited when FVW serves as a source of bioactive compounds, functional food ingredients and biocompatible materials (Papargyropoulou et al., 2014).

It must be noted that the valorisation of FVW is at an early stage of development and that essential elements must be still clarified to assess its viability (Cristóbal et al., 2018; Heck & Rogers, 2014). Firstly, data on the exact amount of waste produced from food processing is nowadays very limited (Pfaltzgraff et al., 2013). Moreover, the resource demand of valorisation strategies as compared to the traditional waste management options should be evaluated. In fact, the implementation of innovative valorisation strategies is viable only if bringing environmental and economic advantages as compared to traditional management strategies. Although not discussing at all these crucial aspects, most of literature studies dealing with FVW valorisation generally assume that FVW valorisation would lead to environmental and economic advantages. However, many of them exploit innovative technologies such as high pressure and supercritical fluid processing, which are well-known to require huge investment and maintenance costs, as well as specialized know-how and plants (Garcia-Gonzalez et al., 2007). Also, even when using commonly available technologies (Talens et al., 2016) an accurate cost-benefit analysis should be performed to evaluate the environmental and economic sustainability of the proposed FVW valorisation strategies (Meullemiestre et al., 2016; Sicaire et al., 2016).

Finally, most studies relevant to feasibility assessment of FVW valorisation do not consider the potential interactions of the proposed valorisation strategy with other possible valorisation pathways or existing waste management options. Nevertheless, the integration of multiple valorisation pathways within the existing waste management system towards a multi FVW biorefinery concept is most likely to represent the real future scenario (Cristóbal et al., 2018; Goula & Lazarides, 2015).

In this regard, the “multi-objective” method described by Simeoni et al. (2018) could represent a valuable tool to estimate the environmental and economic implications related to the integration of FVW valorisation strategies in the traditional waste management system, on an industrial scale. The final aim of this method is the development of a decision support system (DSS), sustaining the decisionmaker in rationally identifying the most sustainable and worthy-of-investment option among a range of many feasible solutions. The application of this method is based on three main phases. Initially, the investigative phase aims at collecting quantitative data on the considered industrial system. Subsequently, in the design phase, input and output variables, their interactions, system constraints and objectives are defined, and combined in multiple scenarios. Finally, in the scenario analysis phase, the latter are scheduled and compared based on the study objectives (Simeoni et al., 2018).

In this work, the potentialities of the multi-objective method in assessing the environmental and economic impact of industrial-scale FVW valorisation were investigated. The study-case of lettuce waste was taken into considerations, since this waste was successfully valorised on a laboratory scale by using both traditional and innovative technologies. In particular, ready-to-drink juices, antioxidant extracts, functional flour and a biodegradable expanded material were obtained by using high pressure homogenisation, ultrasounds, air-drying and supercritical-CO_2-drying, respectively (Plazzotta et al., 2018a, b, c; Plazzotta & Manzocco, 2018a, b). Quantitative data relevant to a hypothetic industrial park integrating these valorisation processes with those commonly applied for lettuce waste management (anaerobic digestion, composting, carbonisation) were collected. Different possible scenarios were then obtained and compared based on environmental and economic indexes related to lettuce waste valorisation activities.

2. Materials and methods

A classical DSS model was applied to lettuce waste valorisation. Its structure consisted of three major phases, whose description and main outputs are described in Figure 1: investigative phase, design phase and scenario analysis (Mattiussi et al., 2014; Simeoni et al., 2018).

2.1 Investigative phase

For the investigative phase, the tools of Life Cycle Analysis (LCA) and techno-economic and profitability assessment were used. All collected data were referred to an annual working period corresponding to 8 working hour/day for 200 working days.

Lettuce waste quantification

A quantitative assessment of the amount of lettuce waste generated by fresh-cut lettuce processing in Italy was performed. Data about fresh-cut lettuce market (M_L) were retrieved from official data and dedicated literature (Casati & Baldi, 2012; Confcoperative, 2016). Data relevant to the percentage amount of waste generated during a typical fresh-cut processing of whole-head lettuce ($\%_{WL}$) were collected in a large Italian company, as described in Plazzotta et al. (2017). The total waste amount annually generated in Italy from fresh-cut processing of lettuce heads (W_L) was thus quantified (eq. 1).

$$W_L = M_L \times \%_{WL} \qquad \textit{eq. 1}$$

Lettuce waste valorisation industrial park

An industrial park integrating traditional lettuce waste management strategies (i.e. anaerobic digestion to produce biogas, composting to produce fertilizers and carbonization to produce biocarbon) with the innovative valorisation options (i.e. high pressure homogenisation to produce fresh juices, ultrasound-assisted extraction of antioxidant polyphenols, air-drying and grinding to produce functional flour, supercritical-CO_2-drying to produce biodegradable expanded materials) was hypothesized. To this aim, the unit operations involved in processes for traditional waste management, innovative waste valorisation and side activities were identified, along with possible interactions among the different processes and mass flows of raw materials, wastes and utilities (energy, water).

Energy demand and costs

Data relevant to nominal energy demand and costs of lettuce waste valorisation plants, integrated into the designed industrial park, were collected. Laboratory-scale data were directly derived from experimental activity, while industrial-scale data were obtained from company surveys. In particular, data relevant to traditional lettuce waste management strategies were collected from sector experts, engaged in the planning of local industrial activities. By contrast, in the case of innovative valorisation strategies, that are not currently present in the market, data collection was based on escalation factors of similar existing plants and equipment (Cristóbal et al., 2018).

Collected data were elaborated to obtain energy functions, describing all the possibilities from a small laboratory scale up to large industrial ones. Regression equations describing the variation of absorbed nominal power as a function of maximum plant capacity were obtained and compared based on the R^2 (Microsoft® Excel 2016). The equation presenting the highest R^2 was selected. Cost functions, describing the variation of equipment cost (C_E, €) as a function of absorbed nominal power were similarly obtained.

According to sector experts' opinion, additional costs for plant design (C_{PD}, €) were calculated as 2% of C_E. The latter was set as 1/3 of the total capital investment (C_I, €), while the remaining 2/3 was attributed to civil work (C_{CW}, €). Thus, C_I was calculated as reported in eq. 2.

$$C_I(€) = C_E + C_{PD} + C_{CW} \quad \textit{eq. 2}$$

The cost of manufacturing (C_M), associated with daily operation of the industrial park, was calculated according to eq. 3:

$$C_M\ (€) = C_{CI} + C_W + C_U + C_{RM} + C_{WS} \quad \textit{eq. 3}$$

where

- C_{CI} (€) is the cost derived from C_I. Costs for unscheduled and regular maintenance, and interest rate per year were calculated as 7.5 and 15% of C_E, respectively (Cristóbal et al., 2018);
- C_W (€) is the cost of workforce required for plant operation. The latter was quantified based on common requirements of local waste management installations and food industries, as defined by experts in the sector. Basic salary was obtained from tables of national collective labour agreements work in the waste management and food sector (CCNL, 2018). The workforce requirement was maintained independent on the lettuce waste amount processed in the industrial park. This simplification was based on the high level of automation of most of the unit operations involved in the

different processes;

- C_U (€) is the cost of utilities. The cost electric power and water, considered as the main utilities, was retrieved from average European prices (EUROSTAT, 2018);
- C_{RM} (€) is the cost of raw materials. It includes (i) the cost of lettuce waste, that was considered negligible, since it has not (yet) a market value; (ii) the cost of chemicals and reactants (i.e. CO_2 and ethanol), that was obtained by a survey on producers (Sigma Aldrich, Milan, Italy); (iii) cost of transport, that was considered negligible, due to the geographic proximity of companies in the considered industrial park;
- C_{WS} (€) is the cost of waste streams. The cost of ethanol, CO_2 and wastewater streams was considered negligible, since they can be purified and recycled in the industrial process, used as fuels in cogeneration systems or incorporated back in the soil for nutrient uptake (Attard et al., 2015).

Environmental advantage and economic effort

Energy saving and reduction of greenhouse gas emissions were set as indexes of the environmental advantage of the designed lettuce waste valorisation industrial park. Saved energy was quantified based on the biomethane-derived energy, obtained from lettuce waste anaerobic digestion (eq. 4):

$$Saved\ energy\ (tons\ of\ oil\ equivalent) = Energy\ from\ biomethane\ (kWh) \times 1.87 \cdot 10^{-4} \qquad eq.\ 4$$

where $1.87 \cdot 10^{-4}$ is the standard coefficient for natural gas conversion into oil equivalent (Simeoni et al., 2018). The reduction of greenhouse gas emissions was also calculated from biogas-derived energy through the proper emission conversion factor of electricity for the Italian electricity production system (Simeoni et al., 2018) (eq. 5):

$$Greenhouse\ gas\ reduction\ (tons\ of\ CO_2) = Energy\ from\ biomethane\ (kWh)\ \times 4.22 \cdot 10^{-4} \qquad eq.\ 5$$

Total investment cost (C_I, eq. 2) and payback time were set as economic effort indexes of the designed industrial park. Payback time (eq. 6) was calculated as the ratio of C_I and the annual net profit:

$$Payback\ time\ (years) = C_I/Annual\ net\ profit \qquad eq.\ 6$$

The annual net profit is calculated based on eq. 7:

$$Annual\ net\ profit\ (€) = R + WhC - C_M \qquad eq.\ 7$$

where R (€) are the revenues obtained from selling the valorisation products in the market, WhC are the "White Certificate" incentives (€) (eq. 8) and C_M is the manufacturing cost (€) (eq. 3). In order to calculate the value of R, the outputs of both traditional and innovative lettuce waste management options were individuated, along with their intended use, unit price range and yield. The output price range was based on that of corresponding products on the market. The yields of each lettuce waste process were estimated as % ratio of final output as compared to the initial amount of raw materials entering the process. To this aim, industrial yields of traditional lettuce waste management options were retrieved from relevant literature (Keeling et al., 2003; Rossi & Bientinesi, 2016). By contrast, in the case of innovative valorisation strategies, laboratory results were scaled up under the assumption that the same yields and performances would be obtained on an industrial scale, given the same processing conditions (Albarelli et al., 2016). *WhC* incentives for saved energy (eq. 4) were also considered as possible sources of economic revenues (Oikonomou et al., 2009) (eq. 8):

$$WhC\ (€) = Saved\ energy\ x\ V_{Whc} \qquad eq.\ 8$$

where V_{WhC} (€) is the value of the incentives, based on the most recent updates (GME-GSE, 2018).

2.2 *Design phase*

The design phase is the core of the used model and is composed by three subsequent stages (Figure 1):

- Design of experiment (DOE). DOE was used to classify the system variables and to define the system constraints. In particular, the following quantities were set as input variables: the initial amount of lettuce waste available for valorisation (W_L, eq. 1); the partition of lettuce waste into traditional waste management options or valorisation processes; the energy demand and cost of lettuce waste processing plants; the price of valorisation outputs; the value of energy saving incentives (*WhC*, eq. 8). The environmental advantage and economic effort indexes identified in the investigative phase were set as output variables: saved energy (eq. 4), greenhouse gas reduction (eq. 5), total investment cost (C_I, eq. 2) and payback time (eq. 6).

  The DOE constraints were based on technical and economic issues. In particular, at least 50% of total lettuce waste was allocated to traditional management strategies, which represent an important source of biogas and fertilizers. Moreover, selected lettuce waste, deriving from removal of spoiled and bruised parts and washing of waste, was set at a value lower than 50% of the initial lettuce waste weight intended for innovative valorisation, due to the possible poor conditions of waste. In addition, a payback time higher than 5 years was not considered, since not economically advantageous (Heck & Rogers, 2014).
- Computation. This stage aimed at calculating the value of output variables as a function of input variable values, under the defined DOE constraints. Computation was carried out using ModeFRONTIER® software (Esteco, Trieste, Italy). The solutions calculated by the software represented the possible scenarios of lettuce waste valorisation.
- Scheduling. The objective of this stage was to order the obtained scenarios according

to the value of the output variables. Scheduling was carried out using MatLab® software (MATLAB R2017a, 64-bit; The Mathworks Inc).

2.3 Scenario analysis

Obtained scenarios were compared and discussed in the light of multiple objectives. In particular, the study aimed at the maximization of environmental advantage indexes (eq. 4 and eq. 5) and at the minimisation of economic effort indexes (eq. 2 and eq. 6).

3. Results and discussion

3.1 Investigative phase

Lettuce waste quantification

To produce value-added derivatives intended for food use, lettuce waste is required to present a high homogeneity level. In addition, waste generation sites should not be very scattered, to facilitate the collection and thus cut both collection and transport costs (Galanakis, 2012). For these reasons, this work was focused on lettuce waste generated in the food processing stage, that can ensure both a high compositional homogeneity and large amount in a reduced number of locations (i.e. the industrial plants).

The first step was thus the collection of data relevant to the amount of lettuce waste generated during fresh-cut processing. Official data report that in Italy the fresh-cut lettuce market amounts up to about 105,300 tons/year (Confcoperative, 2016). Of that, 60% is represented by whole-head lettuces, mainly *Iceberg* lettuce (Casati & Baldi, 2012). A survey conducted in a large Italian fresh-cut company revealed that at least 35% of lettuce head weight is wasted, mainly due to initial operations of external leaves and core removal (Plazzotta et al., 2017). Based on these data, the total amount of waste generated in 1 year in Italy by the fresh-cut processing of whole-head lettuce was quantified in about 23,000 tons. Similarly, the total amount of whole-head lettuce waste generated by the large fresh cut company considered in the survey was evaluated. In this company, about 20,000 tons of lettuce are processed into fresh-cut derivatives. Considering 60% of this value to be represented by whole-head lettuces and 35% waste production, the company would manage every year about 4,200 tons of whole-head lettuce waste.

Lettuce waste valorisation industrial park

The design of an industrial park integrating the innovative valorisation strategies of lettuce waste in the current waste management system was hypothesized. The processes involved in traditional lettuce waste management, in its innovative valorisation and in the side activities of the industrial park are reported in Table S1. Real industrial processes were considered for the process design of traditional waste management strategies (i.e. composting, anaerobic digestion and carbonisation) and side activities (i.e. wastewater treatment, ethanol recycling). Such processes, in fact, are already applied on an industrial scale and present high technological readiness levels (TRL). By contrast, innovative lettuce waste valorisation strategies, based on the production of functional beverages, antioxidant extracts, vegetable flour and biodegradable materials by means of innovative technologies, present a low TRL. For this reason, process design was based on processes carried out on a laboratory scale and escalation factors of similar existing plants.

The hypothesized industrial park is represented in Figure 2, where the flow diagram of the different processes involved in both traditional lettuce waste management options and innovative valorisation strategies, as well as their interactions are reported. Based on information collected from the producers, lettuce waste is commonly subjected to:

- anaerobic digestion to produce digestate (fertilizer), biogas and, in turn, energy (by means of the cogeneration unit) (Garcia-Peña et al., 2011);

- composting to produce fertilizers (Himanen & Hänninen, 2011);
- carbonisation to produce biocarbon (Li et al., 2019).

In this case, lettuce waste would be straight directed to the proper industrial facility. By contrast, the implementation of the innovative valorisation strategies would require a preliminary selection of lettuce waste, to remove spoiled and bruised parts. The latter would be managed by means of composting, anaerobic digestion or carbonisation. On the contrary, the selected lettuce waste could be exploited as raw material to produce different valorisation outputs. It must be noted that the need for lettuce waste selection introduces a high uncertainty in the amount of lettuce waste available for innovative valorisation strategies, since the initial condition of lettuce waste depends on unpredictable factors, such as weather and cultivation conditions. Selected lettuce waste could be subjected to:

- blanching and high pressure homogenisation to produce fresh juices (Plazzotta & Manzocco, 2018b);
- ultrasound-assisted extraction to produce antioxidant polyphenolic extracts (Plazzotta & Manzocco, 2018a);
- air-drying and grinding to produce functional flour intended for functional bakery products (Plazzotta et al., 2018a, c);
- water substitution with ethanol and supercritical-CO_2-drying to produce biodegradable expanded materials for packaging or solvent adsorption applications (Plazzotta et al., 2018b).

In addition, side activities for the purification and recycling of spent resources such as ethanol residue and wastewater were hypothesized.

Possible interactions among the different processing steps involved in traditional and innovative valorisation strategies were also identified. In fact, the integration of innovative strategies in the existing waste management framework is surely most likely to represent the real scenario of lettuce waste valorisation, differently from most available literature studies in which waste valorisation processes are described and analysed without considering their integration in the existing waste management system (Cristóbal et al., 2018). In particular, the attention was focused on the possibility to reduce the need for outsourcing of energy, water and raw material of a valorisation process by using the waste streams of other processes integrated in the industrial park.

Energy demand and costs

Cost and energy functions of equipment required for the various unit operations of the processes involved in the implementation of traditional and innovative lettuce waste management strategies are reported in supplementary Table S1. Such functions allow estimating absorbed nominal power and investment cost of specific plants and equipment as a function of their maximum capacity (tons of processed raw material or semi-finished product). Thus, they represent a flexible tool to describe a wide-range of possible scenarios, according to the available lettuce waste amount. This is of extreme importance, considering the overmentioned high uncertainty about the actual amount of lettuce waste possibly exploitable for valorisation. In addition to equipment cost, supplementary Table S2 and S3 show workforce, raw material and utility costs, calculated as detailed in the Material and Method section. Although these costs are likely to variate in a real context, they were maintained fixed. Even if possibly reducing result robustness, this choice allowed the number of variables in the computing system to be reduced.

Environmental advantage and economic effort

The environmental advantage of the lettuce waste valorisation was attributed to the biogas produced form anaerobic digestion of lettuce waste, which can be used as sustainable resource to partially fulfil the energy requirements of the industrial park, contributing to reduce the emissions of greenhouse gases. In addition, the recycle of resources other than energy within the industrial park would allow reducing the need for outsourcing. In this regard, Table 1 reports the main outputs of the lettuce waste processes, underlying their potential recycle within the industrial park. As an example, the carbon dioxide deriving from the co-generation unit involved in the conversion of biogas from anaerobic digestion in methane, could be used in the supercritical-CO_2-drying of lettuce waste. Moreover, the digestate and the biogas-based energy deriving from anaerobic digestion could be entirely recycled for lettuce cultivation and electrical supply of plants and equipment present in the industrial park, respectively. This strategy integration would not only lead to a higher energy self-sufficiency and independence on primary energy sources (fossil fuels), but also to a negligible cost for waste stream management. Moreover, such strategy integration could also allow increasing revenues of the industrial activity. In this regard, White Certificates (WhC) are an energy efficiency market-based instrument, which acknowledge the energy saving obtained by producers through the implementation of energy efficiency measures (Oikonomou et al., 2009). In this study, WhC were thus considered as possible revenues of the designed industrial park. In particular, a variable value, ranging from 0 to 300 €, was set for WhC, based on most recent updates (GME-GSE, 2018). Besides WhC incentives, the main revenues of lettuce waste valorisation activities would derive from selling valorisation products on the market. In this regard, the yields of innovative valorisation processes of lettuce waste are reported in Table 1. As explained in the Materials and Methods, real industrial data were used for traditional strategies, while yields of innovative processes were based on laboratory data. For example, the yield of air-drying and supercritical-CO_2-drying resulted of 5%, due to 95% moisture content of lettuce waste (Plazzotta et al., 2018a). Similarly, in the ultrasound assisted extraction of lettuce polyphenols, about 20% of solid residue was retained in the filtration step, leading to 80% yield (Plazzotta & Manzocco, 2018a). Table 1 also reports the identified outputs of lettuce waste valorisation strategies, along with their intended use, and the unit price range of corresponding market products. The choice to use a price range rather than a medium price was based on the extreme variability and uncertainty of their values over time (Cristóbal et al., 2018; Giraudet et al., 2011).

3.2 Design phase

In the Design phase, data collected in the investigative step were elaborated to estimate the effect of the variation of lettuce waste amount, lettuce waste partition into the different valorisation process, energy demand and cost of waste valorisation plants, price of valorisation products and WhC incentives on the environmental advantage and economic effort of the lettuce waste valorisation industrial park. The Design phase computed a total of 121,560 possible scenarios. The latter were then scheduled according to the values assumed by the environmental advantage and economic effort indexes of the multi-objective study.

3.3 Scenario analysis

The objectives of this study were the maximization of environmental advantage and the minimisation of economic effort indexes of the lettuce waste valorisation industrial park. Table 2 reports possible scenarios, that were selected based on the achievement of each one of the study objectives. These scenarios took into considerations the amount of whole-head lettuce waste processed during 1 year from a large fresh-cut company (about 4,200 tons, as discussed in paragraph 3.1). As expected, the scenario allowing to maximise the environmental advantage would be the one managing the major part (60%) of lettuce waste through anaerobic digestion to produce biogas. The remaining lettuce waste fraction would be valorised into fresh homogenates, antioxidant extracts and innovative biodegradable materials. However, the investment cost of this scenario would be of 9.7 million € and with a payback time higher than 2 years (Table 2). This can be attributed to the high cost of equipment required for implementing innovative technologies such as high pressure homogenisation, ultrasound assisted extraction and supercritical-CO_2-drying. The minimisation of investment cost would be reached by managing at least 90% of lettuce waste through traditional options, not allowing a proper valorisation of its rich composition. Moreover, this scenario would also present limited environmental advantages and a payback time longer than 3 years (Table 2). The latter would be minimized to just 4 months by valorising 70% lettuce waste into bioactive extracts. This valorisation strategy, in fact, would highly increase the value chain of lettuce waste, by producing a high-price food supplement (Table 1). Nevertheless, investment cost would be higher than 10.5 million €, while reduced CO_2 emissions and saved energy would still be half that those realised in the scenario maximising the environmental advantage of the designed industrial park (Table 2). Therefore, all the scenarios reaching one of the study objectives would present some drawbacks. In this regard, the selection of a specific scenario should be driven by a compromise among the defined economic and environmental objectives. For this reason, a further scenario, deriving from a compromise solution is presented in Table 2. In this scenario, 20% of lettuce waste would be valorised by the application of innovative valorisation strategies, presenting an investment cost lower than 9.1 million € and a pay-back time of about 1 year. The remaining 80% lettuce waste would be subjected to traditional management options, contributing to greenhouse gases emission reduction and energy saving of about 72 tons CO_2/year and 32 tons of oil equivalents/year respectively (Table 2).

3.4 Sources of uncertainty

Although representing a valuable support to decision makers, the conducted study entails a high uncertainty, leading to the need for an accurate validation of obtained results before application in a real context. The main sources of uncertainty of this study are those commonly found in similar estimation approaches, as reported by Cristóbal et al. (2018), and include:

- cost estimation: for low TRL technologies, cost estimation presents a ±30% accuracy, due to possible failures in inflation projection and cost growth due to unpredictable events related to the high complex process and unproven technology (Tsagkari et al., 2016);
- cost of utilities: the electricity and natural gas prices for industrial users in the European Union depend on a range of different supply and demand conditions, including the geopolitical situation, import diversification, network costs, environmental protection costs, weather conditions, and levels of taxation (EUROSTAT, 2018);
- scaling-up variables: laboratory results were used to scale-up the innovative valorisation process considering that the same performance would be obtained. However, this should be carefully evaluated in pilot plants and corrected if necessary;
- start-up issues: in this study, the maximum productivity of processes was hypothesized, without considering possible economic issues of the start-up phase;
- wastes: in the present study, wastes were considered to be fully recycled in the industrial park economy. However, if they cannot be fully or partially used within the system, additional waste management costs should be considered;
- lettuce waste amount: although based on data collected in a real company, the estimation of lettuce waste quantity available for the valorisation is uncertain. Waste amount and quality, in fact, can vary according to unpredictable conditions, including

weather, cultivation yield, pests;

- transport cost: in the present study, transport cost was considered negligible, due to geographical proximity of companies in the industrial park. However, a wider industrial park could be imagined, possibly collecting wastes from the entire country. In that case, transport cost and environmental impact should be computed in the system sustainability assessment.

4. Conclusions

In this study, the “multi-objective” method was applied to estimate the economic and environmental impact of lettuce waste valorisation. The proposed method was demonstrated to be highly flexible, since considering a variable range of waste amount, equipment cost, energy demand, and plant productive capacity. It also allowed considering the integration of innovative valorisation pathways in the existing waste management system, towards a multiple “zero-waste” biorefinery concept.

Although further research is needed for a robust validation of economic and environmental sustainability estimates, the application of the proposed method led to the identification of different rational solutions. The latter could lead either to the maximisation of a specific environmental or economic objective, or to the identification of a compromise among the different sustainability objectives. In particular, the optimal amount of lettuce waste to be diverted from landfilling, anaerobic digestion, carbonisation and composting plants to food industries could be identified, leading to its valorisation under different scenarios.

The acquired results would allow the generation of a flexible decision support tool to guide stakeholders’ and policy makers’ investment in the most sustainable waste valorisation strategies. This tool could be also exploited for promoting advantageous industrial symbiosis opportunities in the waste management sector.

Declaration of interest

All Authors declare no conflict of interest.

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Figure/supplementary figure captions

Figure 1. Structure of the decision support system.

Figure 2. Flow diagram of resources (lettuce waste, ethanol, carbon dioxide, water and energy) in an industrial park integrating traditional management and innovative valorisation strategies of lettuce waste.

Figure S1. Number of publications relevant to fruit and vegetable waste valorisation from 1995 up to 2018. (Data collected from Web of Science databases, Clarivate Analytics, using as key-words "Fruit and vegetable waste" or "FVW" and "valorisation" or "valorization").

Table/Supplementary table headings

Table 1. Yields and outputs of processes involved in traditional management and innovative valorisation of lettuce waste and in related side activities. Output intended use and unit price range are also reported.

Table 2. Possible scenarios of lettuce waste valorisation, according to the main study objectives.

Table S1. Cost and energy functions of equipment and plants required for the various unit operations of processes involved in the implementation of traditional management and innovative valorisation strategies of lettuce waste and in side activities.

Table S2. Cost per unit of raw materials and utilities entering the processes involved in traditional management and innovative valorisation strategies of lettuce waste.

Table S3. Quantification and corresponding salary of workforce required for the various unit operations of processes involved in the implementation of traditional management and innovative valorisation strategies of lettuce waste.